ADVANCED DC/DC CONVERTERS TOWARDS HIGHER VOLUMETRIC EFFICIENCIES FOR SPACE APPLICATIONS

Harry Shaw(1), Jack Shue(2), David Liu(3), Bright Wang(4), Jeannette Plante(5)

(1) NASA, Goddard Space Flight Center, Code 562, Greenbelt, MD harry.c.shaw.1@gsfc.nasa.gov
(2) NASA, Goddard Space Flight Center, Code 563, Greenbelt, MD Jack.Shue@nasa.gov
(3) MEI Corporation, Code 562, NASA GSFC, Greenbelt, MD dliu@pop500.gsfc.nasa.gov
(4) QSS Group, Code 562, NASA GSFC, Greenbelt, MD Bright.L.Wang.1@gsfc.nasa.gov
(5) Dynamic Range Corporation, Code 562, NASA GSFC, Greenbelt, MD jfplante@pop500.gsfc.nasa.gov

ABSTRACT

A new emphasis on planetary exploration by NASA drives the need for small, high power DC/DC converters which are functionally modular. NASA GSFC and other government space organizations are supporting technology development in the DC/DC converter area to both meet new needs and to promote more sources of supply. New technologies which enable miniaturization such as embedded passive technologies and thermal management using high thermal conductivity materials are features of the new designs. Construction of some simple DC/DC converter core circuits using embedded components was found to be successful for increasing volumetric efficiency to 37 W/inch^3. The embedded passives were also able to perform satisfactorily in this application in cryogenic temperatures.

1 INTRODUCTION

DC-to-DC converters are ubiquitous in modern space systems. A typical science satellite carrying two or three primary instruments can use as many as 60 to 100 converters of five or six types. Standard solar arrays are designed to generate output voltages of between 21V (DC) to 48V (DC). DC/DC converters are used to provide output voltages of ±15V, ±12V, 5V, 3.3V, and 1.5V to the spacecraft electronics.

Several factors over the past five years have prompted government space organizations to seek new DC/DC converters. These include: regular ground and in-flight failures of commercial parts, a low number of suppliers and new operating requirements. Of particular interest to NASA's Human and Robotics Technology focus of the Exploration Mission are new power systems and components that have much higher power, fault tolerance and self-health monitoring, manufacturability and modularity than has been used to date. This paper will discuss some new DC-to-DC converter designs to address these future needs.

2. CURRENT AND FUTURE NEEDS

Though many configurations can be used, NASA tends to use phase modulated, switching regulator types of DC/DC converters to supply both digital and analog voltages for the spacecraft and instrument electronics. Though designs realized in a standard printed circuit card format are used occasionally, there is enormous pressure to use hybridized units to benefit from their high level of miniaturization.

In two surveys recently conducted on NASA's use of hybrid DC-to-DC converters the following themes emerge[1]:

a. NASA mainly uses DC/DC converters which support less than 60 W output power
b. Primarily the following output voltages are used: +2.6, +3.3, +5.0, ±12, ±15
c. Input voltages of between 18V and 46V are found with one particular application using a 120V input.
d. Radiation tolerance is needed but not always as high as the "hard" region.

3. CURRENT PROBLEMS WITH DC/DC CONVERTERS USED FOR SPACE

A ledger of failure occurrences of DC-to-DC converters in space applications was kept between the years 1997 and 2001 showing 25 failures in space systems over that time period. Continued instances of catastrophic failure of DC-to-DC converters motivated the NASA GSFC Power Systems Design engineering branch and the Electronic Parts engineering branch to convene a series of meetings to review each other's perspective on the sources of the failures.

A website (http://nepp.nasa.gov/dcdc) was developed to record the lessons learned that came out during those discussions. Some of the more important topics include:

1. Application notes on:
   a. Efficiency Specifications are based on best case conditions
   b. Filtering must be carefully matched to the converter and application
   c. Front End Oscillations – Changes in Vin and Zin
   d. Synchronization and Beat Frequency
   e. Thermal and Mechanical Packaging Design
   f. Optocouplers and their radiation sensitivity
   g. Mass/Volume Estimating; don't forget all the add-ons needed
   h. Testing to the Application Conditions
   i. Establishing the Reliability for a Production Lot of DC-DC Converters
   j. Government vs. Manufacturer Certification
   k. Preventing Internal Packaging Defects
   l. Rectifier Diode Testing In Situ
   m. Application Scenarios Can Affect Radiation Tolerance of Internal Elements
   n. Manufacturing Process Changes During Lot Production
   o. Supply Chain Issues
   p. Use of Single Lot Date Codes
   q. Limits to the use of "Heritage" Qualification Data
   r. Avoiding Damaging Feedback Signals
   s. Floating Case
2. Case Studies of Electronic Packaging Issues and Problems
3. Overviews of Technology Development for JAXA and ESA
4. The previously referenced needs survey .

Many of these issues are related to a lack of knowledge about the internal circuit design of the converters being used and their compatibility with the particular application. The new development activity will provide the insight needed to reduce these problems.

4. CONVERTER DEVELOPMENT BY NASA GSFC

NASA GSFC has supported examination of DC-to-DC converter designs which both seek to maximize volumetric efficiency (W/inch^3) and to demonstrate core configurations with new component technologies for increasingly higher output power and output current.

The results that can be reported thus far include the preliminary results of the design, processing, board assembly, and the initial testing of circuits that address the following technical issues:

(1). Implementation of high thermal conductivity materials for thermal paths and heat sinks

(2). Miniaturization through passive component embedding and by multi-layer circuit stacking.

4.1 Design and Processing Development

Three configurations were built to investigate opportunities for miniaturization. The first two used a simple switched mode DC-to-DC converter circuit provided by an in-house designer. This circuit was built two times exploring the use of aluminum nitride (AlN) substrates alone and AlN integrated with FR4 epoxy-glass printed circuit boards. For the third configuration a heritage circuit was provided from a completed flight project, it was simplified, and was used to demonstrate an AlN-Diamond/Aluminum system which included embedded passives. Fully embedded magnetics were also considered. Electrical and thermal testing was performed to measure thermal behavior and to calculate volumetric efficiency.

The input voltage for the first circuit was 28V and the designed output was 3.5V, 5A at a switching speed of 100 kHz. A pulse width modulator (PWM) driver is used to control a MOSFET switch to regulate the output voltage, which is ripple suppressed with a high power inductor and capacitor. The signal generation part of the circuit is not included in the evaluated circuit. The effective volume of this circuit section is 2.75" x 2.75" x 0.25" = 1.891 inch^3.

The circuit design was baselined by building it on a traditional commercial FR4 laminate. A complete board is shown in Figure 1.

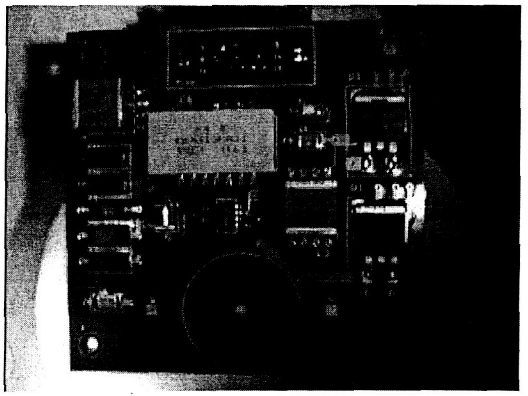


Figure 2. Baseline Board on FR4 Laminate

In order to improve the heat dissipation of the board, a highly thermally conductive aluminum nitride (AlN) substrate was integrated with the FR4 board using brass inter-board columns (Figure 2). The theoretical thermal conductivity of the AlN substrate is ~150 W/m·K which is ~ 7 times better than the thermal conductivity of alumina which is typically used for electronic substrates in multichip modules. All of the surface mount components are assembled on the AlN board whereas the FR4 board provides all the electrical routing. Using this approach, the AlN is directly attached to the heat generating components and acts as a heat sink. AlN's thermal conductivity makes it an excellent choice for transferring the heat to the thermal bus using a number of different types of thermal connections. Figure 3 shows the patterned AlN substrate before lamination and component assembly.

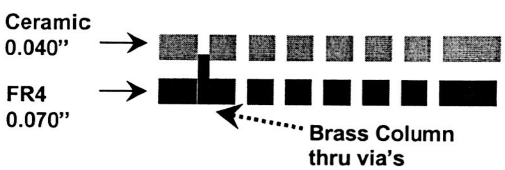


Figure 2. Illustration of AlN laminated to FR4 board using inter-board columns

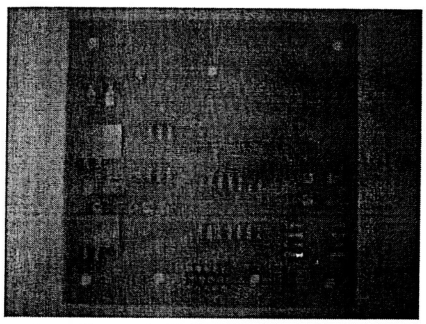


Figure 3. A patterned AlN substrate before lamination

The second approach used was to attach a heat sink made of diamond aluminum composite underneath the AlN substrate (Figure 4). The Diamond/Al material is electrically conductive (resistivity of 2-6 $\mu\Omega$/cm) with metal-like mechanical properties. This allows it to be machined into complicated shapes that may be needed for installation into complex enclosures or for creating specialized features for the thermal connections. For ground systems this enables machining fin shapes which are used with fan cooling.

4.2 AlN-FR4 Assembly Electrical Performance

Table 1 summarizes the preliminary results for the test circuit on the FR4 board (baseline) and again on the AlN-FR4 laminate. The measurements were conducted at room temperature with a relative humidity of 44% with no connection to thermal ground except through the bottom of the assembly to the ESD bench. A PWM driver input of 12.5V square wave is generated from an external pulse/function generator with an input voltage of 28V. The designed voltage and current output of 3.5V and 5A respectively, corresponding to an output power of 17.5W, was achievable with the baseline assembly however a significant component temperature

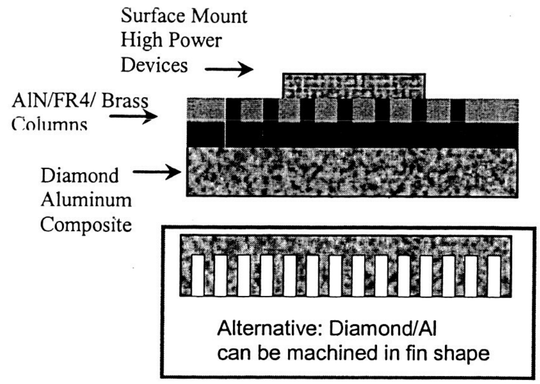


Figure 4 Implementation of AlN and Diamond/Al as a thermal path and a heat sink

increase was observed (60.1°C for D1). The temperature increase for the AlN-FR4 assembly was 31.6°C. Both the FR4 board and the FR4/AlN assembly showed efficiency reduction when the test frequency was increased from 50 kHz to 100 kHz. This is expected due to high frequency inefficiencies of the high power inductor and capacitors.

Table 1. Measurement Results of Testing Circuit on FR4 and FR4+AlN Laminates

	FR4	AlN	FR4	AlN	FR4	AlN
Sw F (kHz)	50	50	100	100	50	100
Vin (V)	28	28	28	28	28	28
Iin (A)	0.83	0.81	0.85	0.84	1.37	1.38
Vo (V)	3.5	3.45	3.49	3.46	3.39	3.36
Io (A)	5.09	5.04	5.08	5.02	8.03	8
Pi (W)	23.24	22.68	23.8	23.52	38.36	38.64
Po (W)	17.82	17.39	17.72	17.73	27.22	26.88
Eff (%)	76.66	76.67	74.49	74.1	70.11	69.56
Meas'd Temp (°C) Q1/D1/L1	43.5/ 60.7/ 33.9	31.2/ 31.6/ 35.4	48.1/ 70.4/ 32.2	31.3/ 32.3/ 32.4	48.1/ 48.2/ 40.1	52.6/ 53.6/ 41.0

Even though a temperature reduction in the high current components was observed for the FR4/AlN assembly, the overall temperature of the AlN board was higher than that of the FR4. This demonstrates the improved thermal conductivity and thermal capacity of the AlN over the FR4 material and the need for an engineered thermal path from the AlN to the thermal bus.

4.3 AlN-FR4 Volumetric Efficiency

Table 2 summarizes the volumetric efficiency of the test circuit under various testing conditions. Performance of 9.59 W/inch^3 has been achieved under current testing conditions. This value can be improved by using a smaller volume inductor core. The output current can also be increased to 10-15A, which increases the value to 18.49 W/inch^3.

Table 2. Volumetric Efficiency of the testing Circuits

	SW. FREQ (kHz)	Po (W)	Elec. EFF. (%)	Vol. Eff. (W/inch^3)
FR4	50	17.82	76.66	**9.43**
AlN	50	17.39	76.67	**9.20**
FR4	100	17.72	74.49	**9.37**
AlN	100	17.73	74.10	**9.37**
FR4	50	27.22	70.11	**14.40**
AlN	100	26.88	69.56	**14.22**

In order to improve the volumetric efficiency, the AlN board was redesigned to support much higher current levels using high current pins and widened traces. The traces on the FR4 board were moved to the top of the AlN board. These improvements resulted in a three-fold improvement in volumetric efficiency. Figure 4 shows the second version of the AlN circuit board before and after it was populated.

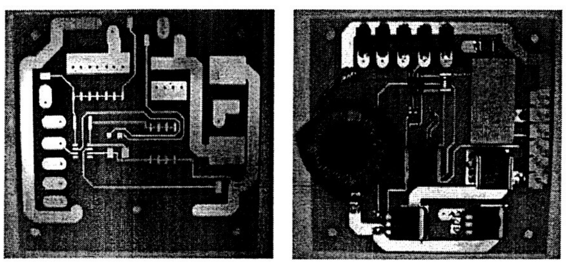


Figure 4. Modified circuit board on AlN improving the volumetric efficiency

Table 3. Volumetric Efficiency of the Improved AlN Assembly

	SW. FREQ (kHz)	OUTPUT POWER (W)	Elec. EFF. (%)	Vol. Eff. (W/inch^3)
AlN	100	27.38	76.67	**14.48**
AlN	100	34.20	74.10	**18.09**
AlN	100	40.97	70.11	**21.67**
AlN+ Heatsink	100	51.30	69.56	**27.13**

4.4 Diamond/Aluminum Composite Assembly Electrical Performance and Volumetric Efficiency

MER Corporation has demonstrated a new material technology under a NASA –funded SBIR project. This project develops passive cooling systems for power electronics based on its Diamond/Al composites. The process uses high-pressure squeeze casting to fabricate the material. The ratio of diamond powder to aluminum can be specified in order to control CTE to match design needs. This design used a 50%/50% ratio. The process is by cast molding allowing the shape to be user defined. The composite material exhibits excellent thermal properties with relatively low density, which results in weight reduction for the high power electronics in space applications. Table 4 summarizes the thermal characteristics in comparison to some other highly thermally conductive materials. The finished surface can be made as flat as ±6μm over a distance of 35 mm.

Table 5. Comparison of Diamond/Al to other high thermal conductive materials

Description	Thermal Conductivity (W/m ·k)	CTE (ppm/K)	Density (g/cm^3)
85W/15Cu wt%	180	7.2	16.2
Diamond/Al	**550-650**	**7.5**	**3.10**
Al Metal	190	24	2.78
Cu Metal	395	19	8.96

A 50/50 Diamond/Al composite plate (4" x 4" x 0.5") with a fin design (Figure 5) was solder-mounted to the pre-fabricated AlN substrate (figure 4) to form a test assembly.

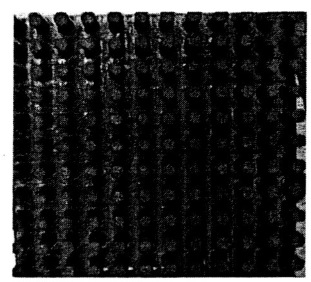


Figure 5. Molded Aluminum-Diamond heat sink

Table 6 summarizes the electrical test results for the AlN circuit board fabricated attached to a 4" x 4" x 0.75" Al plate and to the Diamond/Al composite heat sink.

5.0 Use of Embedded Passives

The previous work was focused on implementing high thermally conductive materials in both the circuit substrate and the heat sink to improve the heat dissipation. Overall circuit miniaturization was also explored to increase the volumetric efficiency.

We obtained a 5A, 40W DC/DC current source circuit design from a prior NASA project external to GSFC. This design consisted of more than 5 functional blocks with total of more than 269 components and had

Table 6. Volumetric Efficiency of the AlN with Diamond/Al HS

		AlN + 4x4x¾" Diamond/Al HS	AlN + 4x4x¾" Diamond/Al HS
Vin (V)		28.02	35.02
Iin (A)		2.35	2.68
Io (V)		3.4	3.41
Io (A)		15.04	20.54
Pi (W)		65.85	93.85
Po (W)		51.14	70.04
Vol. Eff. (W/Inch^3)		27.05	37.06
Elec. Eff. (%)		77.66	74.63
Meas'd Temp (°C)	Board Center	60.5	69.6
	Q1 Case	50.8	63.4
	D1 Case	51.3	60.3
	L1 Core	61.3	75.6

functional and flight heritage. Several of the functional blocks were either removed or simplified and rebuilt using component embedding and high thermal conductivity materials. The performance of the second circuit with embedded components in shown in Table 7.

5.1 Magnetic Embedding

The ability to embed transformers and inductors is still in its infant stage, primarily due to the mutual inductance among adjacent embedded magnetic components. This problem complicates the inductor embedding technology when specified inductance values are to be achieved.

In this program, considerable attention was given to the task of embedding magnetic components into the PCB boards and two approaches have been identified. One, using embedded traces and clamshell ferrites, was used in bread boarding a second in-house design. The other is illustrated below and has been negotiated with a commercial board house but not yet built (Figure 8).

6.0 CRYOGENIC CHARACTERIZATIONS

Of great interest to the new Human and Robotic Technology program is the performance of power system components at cryogenic temperatures. To investigate the performance, the AlN assembly of Figure 4 was cooled down to –168°C (liquid nitrogen) and maintained for 8 hours. The circuit performance was measured every hour. Table 7 summarizes the test results as function of soak time. The results show that initially the circuit performed normally at low temperatures. After approximately eight hours the input power began to rise, the efficiency tracked the input power rise through its decrease, and the output

Table 7. Performance of the Two Miniaturized Designs

		Converter Board from Fig. 1	**13W Forward Converter**
Vin (V)		28.02	28.14
Iin (A)		3.75	0.68
Vout (V)		3.3	2.5
Iout (A)		22.8	5.04
Pin (W)		105.01	19.14
Pout (W)		75.31	12.6
Elect Effic. (%)		71.67	65.8
Vout Ripp (mVpp)		52.2	100
Meas. Temp (°C)	Main MOSFET	47.6	56.8
	Flywheel MOSFET	50.1	77.4
	Forward MOSFET	N/A	74.5
	Main XFMR	57.4	45.6

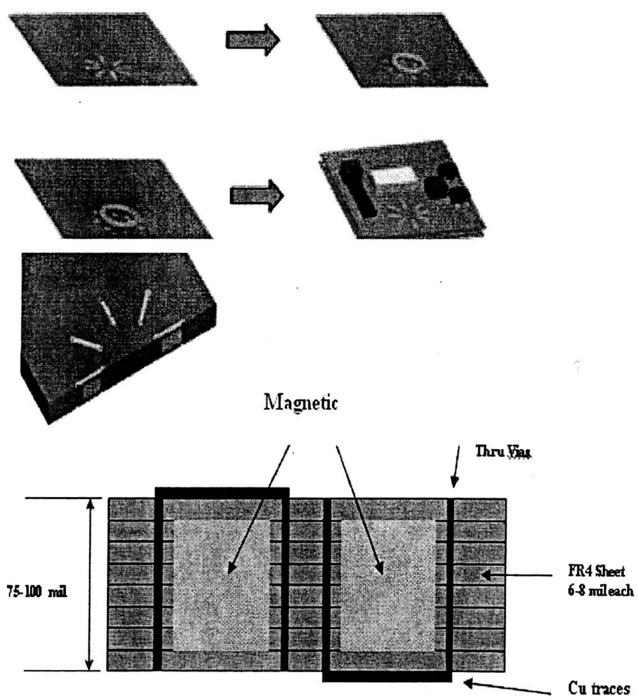
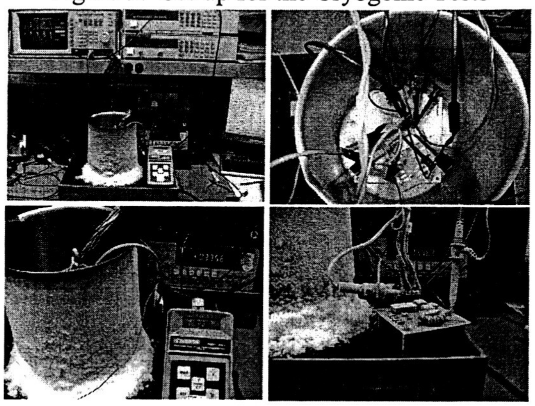


Figure 8. Concept for Embedding Magnetic Cores into Multi-layer PCB.

ripple when out of specification. This point in the test is noted by the Red font at the end of Table 8. This performance believed to be due to the failure of the five parallel solid tantalum chip capacitors. Photographs of the device under test are shown in Figure 9.

Figure 9. Set-up for the Cryogenic Tests



7.0 SUMMARY

A central clearinghouse for lessons learned about DC/DC converters used in space systems is now available and invites insightful and focused additions from the space community. Internationally, government space organizations have recognized that there is a value in expanding the sources of supply for DC-to-DC converters. NASA is especially interested in higher power designs for future planetary exploration missions.

Several simplified converters have been built on various thermal platforms and with embedded components and have been driven to their maximum output power and output current levels achieving a 3 times improvement in volumetric efficiency, a 10 times improvement in geometric miniaturization and a 70% weight reduction. Low temperature performance data was also produced.

Continued effort will be directed at this project in order to a.) continue to push up volumetric efficiency by increasing the output current while maintaining good electrical efficiency, b.) increase the integration of the magnetic components with the PC board and c.) continue to steer electronic part selection for robustness with high current and temperature.

Table 8. Electrical characterization as a function of soak time at cryogenic temperature

TEST CONDITION	Iin (A)	Vo (V)	Pi (W)	Po (W)	Effic (%)	Vo Ripple (mV p-p)
room temp	1.562	**3.31**	43.7	33.1	75.7	450
7:45 am	1.511	**3.32**	42.3	33.2	78.4	225
8:45 am	1.509	**3.30**	42.3	33.0	77.9	220
9:50 am	1.511	**3.32**	42.4	33.3	78.5	220
10:48 am	1.513	**3.34**	42.5	33.4	78.6	150
11:50 am	1.508	**3.33**	42.3	33.3	78.7	140
12:55 pm	1.514	**3.33**	42.5	33.4	78.1	140
1:50 pm	1.513	**3.31**	42.5	33.1	78.0	130
2:50 pm	1.515	**3.32**	42.5	33.2	78.1	130
3:37 pm	**1.624**	3.23	**45.6**	**32.3**	**70.9**	**230**

Table Notes:

1. Input voltage (28.02 V) varied less than 0.2% over the duration of the test
2. The duty cycle was held at 16% for the duration of the test.
3. The output current was also stable at 10A throughout the test.

REFERENCES

1. Tanaka, Shoji, “Comparison of DC/DC Converter Needs for Space Use”, NEPP Website DC/DC Portal (http://nepp.nasa.gov/dcdc), 2004